Nuclear Transparency in Heavy Ion Collisions at 14.6 GeV / nucleon

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The probability of a projectile nucleon to traverse a target nucleus without interaction is calculated for central Si-Pb collisions and compared to the data of E814. The calculations are performed in two independent ways, via Glauber theory and using the transport code UrQMD. For central collisions Glauber predictions are about 30 to 50% higher than experiment, while the output of UrQMD does not show the experimental peak of beam rapidity particles.

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The dynamics of a heavy ion collision is a complicated many-body problem. It is the task of appropriately designed experiments to isolate one particular aspect of the dynamics and elucidate its physics. Wounded nucleons are one of the open problems. In a heavy ion collision a nucleon may undergo a sequence of collisions, which follow so rapidly one after another, that the nucleon is no more in its ground state, even not necessarily in any definite excited baryonic resonance (like Δ or N^*). We will speak of a wounded nucleon. In a next encounter with another nucleon this wounded nucleon will not interact with the free space NN cross section σ_{in}^{NN} but with an effective one $\sigma_{\rm eff}$. Is it possible to determine $\sigma_{\rm eff}$ from experiment?

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The E814 collaboration has designed an experiment which may answer this question [1]. At the energy of 14.6 GeV/nucleon, the projectile ^{28}Si collides with Al, Cu and Pb and the beam rapidity nucleons are studied as a function of the centrality of the reaction (controlled by a measurement of the transverse energy). The beam-rapidity nucleons belong to the projectile and have not lost any energy in the reaction. Of course, in a peripheral reaction one always has the so called spectator nucleons, which never hit the target nucleus. They are not interesting for our purpose. However, in a central event, e.g., for Si on Pb, one still sees beam rapidity nucleons, i.e., nucleons of Si which go through the target nucleus without energy loss. The target nucleus is transparent for these projectile nucleons. We expect the transparency of a heavy nucleus like Pb to be small. Indeed, the "survival probability" S for a projectile nucleon to pass through the target without any inelastic interaction has been measured to $S_{exp} = 3.5 \times 10^{-3}$ for central Si-Pb collisions [1]. Does this result contain information about wounded nucleons and effective NN cross sections?

We proceed in the following ways: The transparency is calculated *without* assuming any exotic phenomena and then the quality of agreement with experiment is judged. We use two complementary methods of calculation

– Glauber theory, in which the physics and formalism is simple and transparent, though not always realistic;
– Cascade calculation (UrQMD), which represents present-day state-of-the-art and may be compared to earlier calculations (Bass et al. [2]).

The survival probability S for a projectile nucleon to pass through the target without inelastic interaction is calculated in a Glauber-type approximation (straight trajectories, frozen nucleons) as

$$S_G(b, \sigma_{\rm eff}) = \int \mathrm{d}^2 s T_p(\vec{b} - \vec{s}) e^{-\sigma_{\rm eff} A_t T_t(\vec{s})}, \qquad (1)$$

where $\vec{b}$ is the impact parameter of the nucleus-nucleus collision, $T_p(b)$ and $T_t(b)$ are the thickness functions ($T(b) = \int dz \rho(b, z)$, $\int d^3 x \rho(x) = 1$) of projectile and target, respectively. The straight line geometry is certainly justified for the through-going nucleons. The use of "frozen" nucleons and the neglect of any other degrees of freedom, like mesons, need justification. We consider a target nucleon and estimate the time Δt in its rest system which has elapsed between the arrival times of the first and the last projectile nucleons: $\Delta t \leq 2R_p/\gamma_p$ where $2R_p \simeq 7$ fm is the diameter of the Si projectile and $\gamma_p \simeq 16$ is the Lorenz factor for the experiment under consideration. The time $\Delta t \approx 0.5$ fm/c is rather short: (i) The target nucleon has not moved significantly in space (frozen approximation is good). (ii) According to the uncertainty principle the intrinsic excitation energy is uncertain

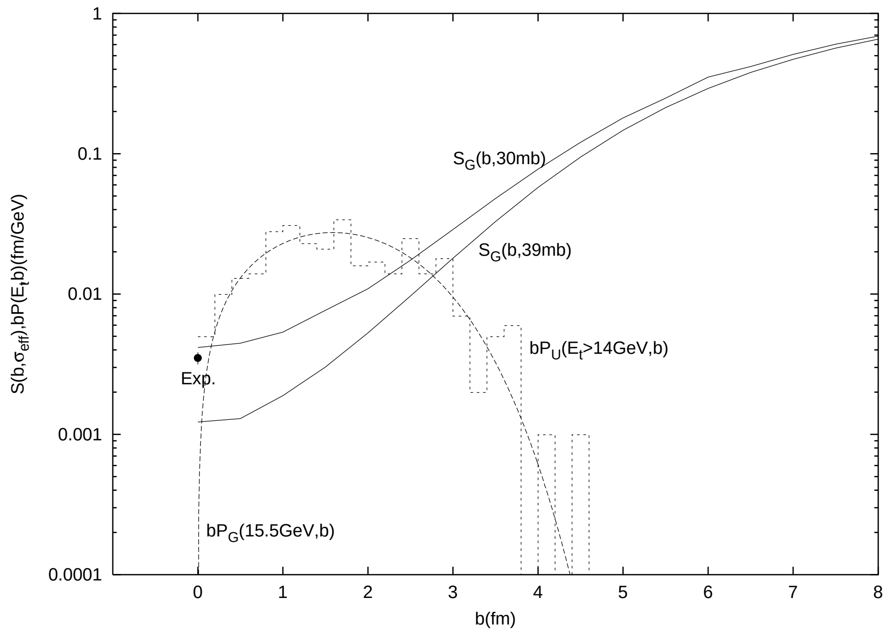

Fig. 1. Survival probabilities $S_G(b, \sigma_{\rm eff})$ of a beam rapidity nucleon calculated in Glauber approximation for $\sigma_{\rm eff} = \sigma_{in}^{NN} = 30$ mb and $\sigma_{\rm eff} = \sigma_{tot}^{NN} = 39$ mb (solid lines), and the experimental value S_{exp} for the survival probability for $E_t^c = 15.5$ GeV. The correlation function $P(E_t, b)$ between transverse energy E_t and impact parameter b is (i) calculated in Glauber approximation, $P_G(E_t, b)$ (continuous line), and (ii) deduced from the results of UrQMD, $P_U(E_t, b)$ (histogram), both plotted as bP in order to represent dσ/db.

by $\Delta E \geq (\Delta t)^{-1} \approx 0.4$ GeV and does not allow the assignment of a definite excited state. (iii) Secondary hadrons are not yet formed since typical formation times are of order 1 fm/c.

The value of the transparency S in Eq. (1) depends on the effective cross section $\sigma_{\rm eff}$. Using Saxon-Woods parameterizations for the densities ρ_t and ρ_p with the surface thickness $a = 0.52$ fm for all nuclei and the half-density radius r_A such that the root-mean-square radius of the nucleus equals the charge radius [3], the survival probability $S(b, \sigma_{\rm eff})$ is calculated for two values $\sigma_{in}^{NN} = 30$ and $\sigma_{tot}^{NN} = 39$ mb which correspond to the inelastic NN cross section and the total one at this energy, respectively. The results are displayed in Fig. 1. The experimental point, measured at transverse energy $E_t^c = 15.5$ GeV is also shown in the figure. It is obtained from the measured mean multiplicity $\langle M_c \rangle$ of beam rapidity protons by

$$S_{exp}(E_t) = \langle M_c \rangle (E_t)/Z, \tag{2}$$

where $Z = 14$ is the number of protons in Si. We have assumed – as the authors of the experiment do – that the highest E_t^c-bin corresponds to a central collision which is assigned a value $b = 0$. Then the experimental value is close to the curve $\sigma_{\rm eff} = 30$ mb. In fact the equation $S_G(b = 0, \sigma_{\rm eff}) = S_{exp}(E^c_t = 15.5$ GeV) leads to a value $\sigma_{\rm eff} = 31.1 \pm 0.7$ mb. This result reproduces a similar calculation using uniform density distributions by the E814 collaboration [1], who have concluded that $\sigma_{\rm eff} = \sigma^{NN}_{in}$ within error bars and no anomaly being visible.

The crucial step in the argument is the assignment of $b = 0$ to the highest E_t-bin. Actually, a given value of E_t selects a distribution of impact parameters only within a band $\Delta b(E_t)$ which is quite large. We study the relation between E_t and b and Δb in the form of a probability distribution$P(E_t, b)$, which gives the probability that values of $\vec{b}$ contribute to events with a given value of E_t. We normalize it as $\int dE_t P(E_t, b) = 1$. With this function and the differential inelastic heavy ion cross section $\mathrm{d}^2\sigma_{in}/d^2b$, one can obtain the dependence of the survival function $S(E_t, \sigma_{\rm eff})$ as a function of the transverse energy

$$S(E_t, \sigma_{\rm eff}) = \frac{\int d^2bS(b, \sigma_{\rm eff})P(E_t, b)d\sigma_{in}/d^2b}{d\sigma_{in}/dE_t}, \tag{3}$$

where

$$\frac{d\sigma_{in}}{dE_t} = \int d^2bP(E_t, b)\frac{d\sigma_{in}}{d^2b}. \tag{4}$$

We will use Eq. (4) to determine $P(E_t, b)$ from a comparison with the measured transverse energy distribution $d\sigma_{in}/dE_t$. With a reasonable Gaussian parameterization of $P_G(E_t, b)$ for the Glauber calculation (or with $P_U(E_t, b)$ from a UrQMD calculation, see below), $S(E_t, \sigma_{\rm eff})$ can be determined from Eqs. 1 and 3 without ambiguity. We discuss our parameterizations.

The inelastic cross section $\mathrm{d}^2\sigma_{in}/d^2b$ is taken from the folding model

$$\frac{d\sigma_{in}}{d^2b}(b) = 1 - exp[-\sigma^{NN}_{in} A_p A_t \int d^2sT_p(\vec{b} - \vec{s})T_t(s)]. \tag{5}$$

The parameterization of $P(E_t, b)$ is more model dependent, and we calculate it in two ways: (i) in the formalism of Glauber theory, and call it $P_G(E_t, b)$, and (ii) deduce it from results of the cascade calculation, $P_U(E_t, b)$. To calculate P_G we assume a Gaussian parameterization

$$P_G(E_t, b) = \frac{1}{\sqrt{2\pi\sigma^2_t(b)}} exp\{-\frac{[E_t - E_t(b)]^2}{2\sigma^2_t(b)}\}, \tag{6}$$

which satisfies the normalization condition. We make the usual assump-

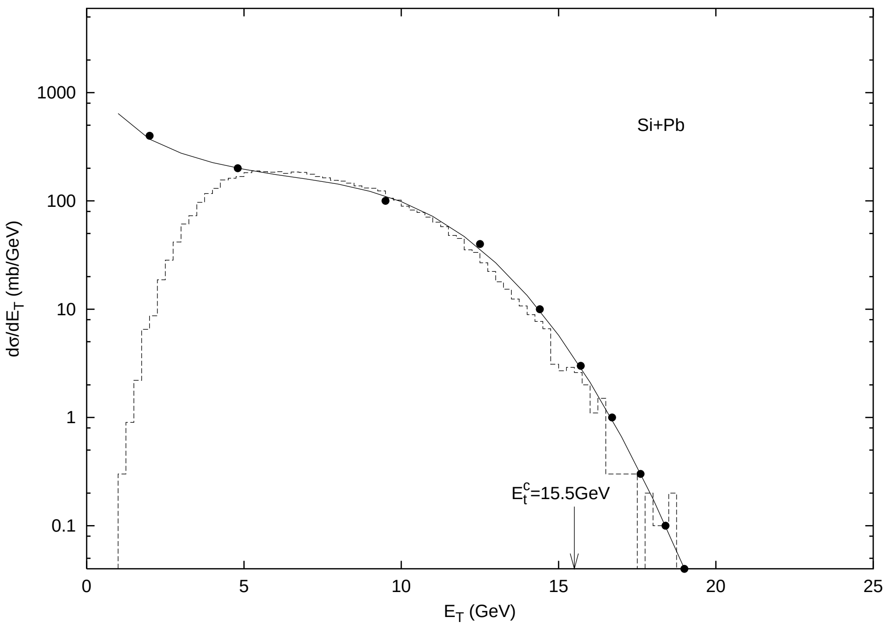

Fig. 2. Transverse energy distributions in the rapidity range $-0.5 < \eta < 0.8$ for Si+Pb collisions at 14.6 GeV / nucleon. Data points (dots) are taken from [7]. The solid line is calculated within the collision model with parameters ϵ_0, ω determined by a fit to the Pb data. The UrQMD calculation (histogram) contains a simulation of the leakage of the TCAL counter as explained in the text.

tions [4,5] for the functions $E_t(b)$ and $\sigma_t(b)$

$$E_t(b) = N(b)\epsilon_0, \tag{7}$$

$$\sigma_t^2(b) = N(b)\epsilon_0^2\omega. \tag{8}$$

Here $N(b)$ is calculated in the "collision model" [4]

$$N(b) = \sigma_{in}^{NN} A_t A_p \int d^2b T_p(\vec{s}) T_t(\vec{b} - \vec{s}), \tag{9}$$

which equals the mean number of NN collisions in a projectile-target interaction with impact parameter b. The proportionality constant ϵ_0 between the observed transverse energy E_t and $N(b)$ depends on the dynamics of hadron production, but also on the experimental set up (chosen rapidity interval and acceptance of counter). It will be a fit parameter. The ansatz $\sigma_t^2 \propto N(b)$ corresponds to the hypothesis that the fluctuations in $N(b)$ are of statistical origin. It is known, however, that the proportionality constant ω in Eq. (8) depends strongly on the rapidity interval of the accepted particles [4]. The reason is not clear [6]. We take ω as a free parameter.

Using expressions (5) to (8) we have calculated $d\sigma_{in}/dE_t$ and have varied the parameters ϵ_0 and ω until the data for Si-Pb are fitted. The result is

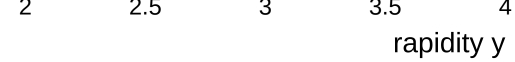

Fig. 3. The rapidity distributions $d\sigma/dy$ for protons and neutrons with $p_t < 0.3$ GeV/c for three intervals of transverse energy E_t. The data are indicated by dots, the calculations using UrQMD are represented by histograms. In each figure the histogram with higher values corresponds to ideal acceptance, the lower, hatched histogram is obtained with E814 acceptance cuts. Beam rapidity is at $y = 3.44$, where the data show a clear peak while the calculation does not show one for the two higher E_t bins.

shown in Fig. 2 with $\sigma_{in}^{NN} = 30$ mb, $\epsilon_0 = 0.067$ GeV, $\omega = 7.8$. A calculation of $N(b)$ in Eqs. (7-8) within the wounded-nucleon model [5] gives a similarly good fit to the data for $d\sigma_{in}/dE_t$.

According to Eq. (3), $P(E_t, b)$ determines the integration region in impact parameter b, which contributes to the integral for a given value of E_t. Fig. 1 shows the distribution $bP_G(E_t, b)$ for a central collision ($E_t^c = 15.5$ GeV) derived in the Glauber formalism, and the corresponding one, $bP_U(E_t^c, b)$, calculated (see below) with the help of the code UrQMD [8]. Both distributions agree within statistics, with a peak around 1.7 fm with a half width of about 2.5 fm. Using the functions $S_G(b, \sigma_{\rm eff})$ and $P_G(E_t^c, b)$ as shown in Fig. 1, the calculated value of $S_G(E_t^c, \sigma_{\rm eff})$ gets contributions from a considerable range of values of b. We find

$$S(E_t^c, \sigma_{\rm eff} = 30{\rm mb})/S_{exp} = 3.47 \tag{10}$$

The calculated transparency is too large by a factor of three.. Should one rather use $\sigma_{\rm eff} = \sigma_{tot}^{NN}$ instead? We think yes: Although elastic scattering changes the rapidity of the projectile nucleon only marginally, it increases the transverse momentum of a nucleon, and an elastically scattered nucleon is not accepted within the experimental window $p_t < 0.3$ GeV with a large probability. The results of the Glauber-type calculations are compared with experiment in Fig. 4. We discuss this figure after we have described the second approach.

The UrQMD calculations presented in this paper are based on the standard version 1.1 [8]. As mentioned in [1], due to leakage in the TCAL [7], there is less than half of the E_t visible. This has two consequences:

(i) The E_t scale of the data cannot be directly compared with that of the cascade calculation. (ii) The data have additional fluctuations, visible as a flatter slope of the E814 E_t-distribution beyond the knee. Simulating the leakage in the Monte Carlo by simply selecting only 37% of the particles hitting the TCAL fixes both problems. The resulting E_t-distribution agrees quite well with the data (Fig. 2). In order to compare to the E_t-selected proton rapidity distributions of E814, we have used the absolute cross section given there – 593, 102 and 6.9 mb – for the three centrality bins shown in

Fig. 4. Comparison of experimental and theoretical results for the multiplicity of beam rapidity protons as a function of transverse energy E_t for the reaction Si+Pb at 14.6 GeV/nucleon. Two methods are employed to characterize "beam rapidity protons" in experiment and in the output of UrQMD: (i) protons with rapidity $y > 3$ (black circles for the data and triangles for UrQMD) and (ii) multiplicity of protons with $y > y_B(3.44)$ multiplied by a factor 2 (open circles for the data and squares for UrQMD). The dashed and solid lines represent Glauber calculations with $\sigma_{\rm eff} = \sigma_{in} = 30$ mb and $\sigma_{\rm eff} = \sigma_{tot} = 39$ mb, respectively.

Fig. 3. The mean impact parameters for these bins are 3.6, 2.1, and 1.6 fm, resp., in UrQMD.

Fig. 3 shows the rapidity distributions for protons + neutrons for the three E_t bins. The data points are shown by the dots, while the two histograms represent the results of the UrQMD calculation with an upper cut in p_t at 0.3 GeV/c. The two histograms show results assuming either perfect acceptance or taking the E814 experimental acceptance cut into account (hatched area). The two histograms are rather similar in the region of beam rapidity ($y_B = 3.44$). While calculations agree with the data in the interval $6 < E_t < 11$ GeV, there is a clear discrepancy in the region around beam rapidity for the two other E_t intervals (middle and lower picture): The calculations do not show any peak, while the data do.

Fig. 4 shows a comparison between experiment and our two calculations for the multiplicity of beam rapidity protons. In the analysis of the data and in the output of UrQMD, two different criteria are employed to characterize "beam rapidity protons": (i) all protons with $y > 3$ (black dots for the experiment and triangles for the UrQMD calculation); (ii) twice the number of protons with $y_B > 3.44$ - assuming the distribution to be symmetric around y_B (open circles for the experiment and black squares for the UrQMD calculation). While the two criteria do not give very different results for the experiment, they lead to very different values for UrQMD up to a factor of five smaller for the second method. This reflects the fact already observed in Fig. 3 that UrQMD does not produce a peak at beam rapidity for the more central values of E_t. It is therefore not meaningful to compare data and results from UrQMD for $E_t > 10$ GeV. For values of $E_t < 10$ GeV calculation and data agree to better than a factor of two – the calculations are above the data for $E_t = 5$ GeV and below the data at $E_t = 10$ GeV. The result of the Glauber calculations (solid curve for $\sigma_{\rm eff} = \sigma_{tot} = 39$ mb, dashed curve $\sigma_{\rm eff} = \sigma_{in} = 30$ mb) are nearly always above the data. The solid curve agrees within 30-50% for central values of E_t, but agreement worsens towards smaller values of E_t. At $E_t = 5$ GeV the Glauber calculation is a factor 3 higher than the data. Note that in this region also the results of UrQMD lie above the data by a factor of 1.5. These discrepancies may partly have the following origin: Small values of E_t correspond to peripheral reactions with several nucleons being spectator particles. All spectator nucleons are included in the calculations; spectator nucleons bound in deuterons, alpha particles etc., however, are not contained in the data.

In summary, the two theoretical approaches, Glauber theory and UrQMD, applied to the transverse energy dependence of the nuclear transparency, have yielded only a semi-quantitative understanding of the data. At small values of E_t (peripheral reactions) calculations are systematically above the data. In the interesting regime of central collisions, Glauber theory predicts values of 30 to 50% above the data, while UrQMD shows clearly no peak of beam-rapidity particles so that the results are only an upper limit.

Although the theoretical situation is still far from being satisfactory the analysis of beam-rapidity particles in heavy ion collisions may potentially be a good way to investigate the question of effective cross sections of wounded nucleons.

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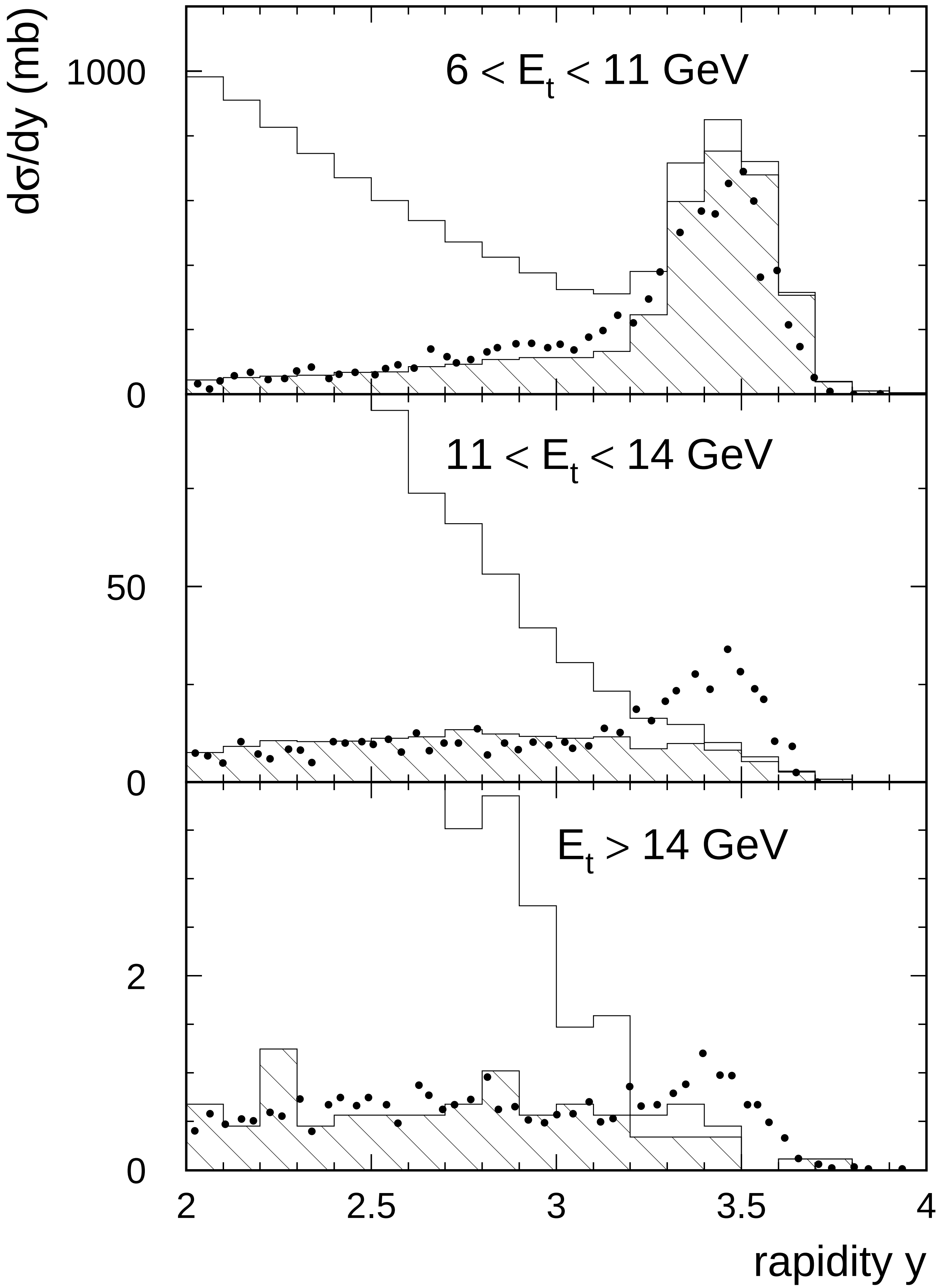
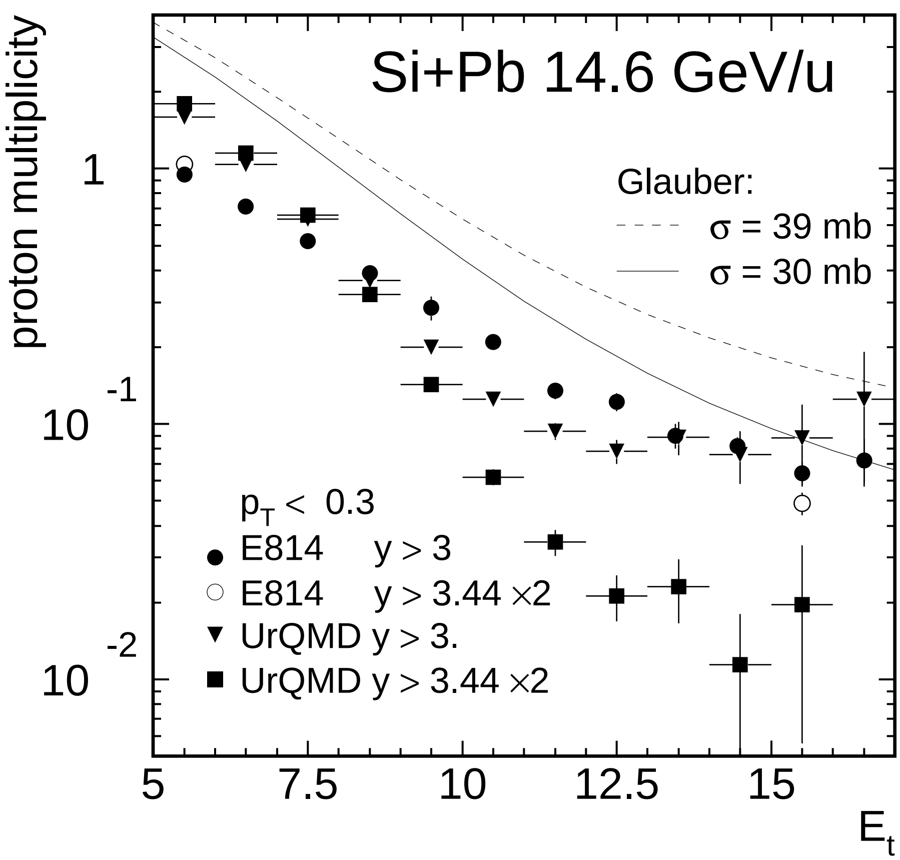


dσ/dy (mb)
1000
0
50
0
2
0
6 < E$_t$ < 11 GeV
11 < E$_t$ < 14 GeV
E$_t$ > 14 GeV
2
2.5
3
3.5
4
rapidity y



Si+Pb 14.6 GeV/u
proton multiplicity
Glauber:
σ = 39 mb
σ = 30 mb
p_T < 0.3
E814 y > 3
E814 y > 3.44 ×2
UrQMD y > 3.
UrQMD y > 3.44 ×2
1
10^-1
10^-2
5
7.5
10
12.5
15
E_t